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SOME PROBLEMS OF MEASURING CURRENT VELOCITY BY THE DOPPLER METHOD /146*

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ABSTRACT. Flow velocity measurements, with an improved Doppler meter combined with a hydrodynamic velocity transformer, for determining the proper motion of a suspension relative to a liquid, are described, with block and circuit diagrams of the device. Equations are given for defining the velocity gradient independently of the mean flow velocity, to permit measurements in drift and sounding. Optimum values for the angle Θ in the Doppler shift formula are derived to define maximum accuracy of the system.

One of the principal questions in the study of the hydrodynamic processes in oceans and seas is the measurement of the velocity field. There are many methods of measuring the flow velocity, based on the most varied principles. Each of them has advantages and disadvantages relative to the others. One is the method of measuring the velocity of a flow relative to the instrument based on the recording of the Doppler frequency shifts of radiation scattered by water, which deserves notice. This method has many favorable features, for instance, linearity, inertialessness, self-calibration, broad dynamic range, continuous recording, and absence of moving parts. The flow velocity is also measured at a certain distance from the instrument, without perturbing the volume of liquid being measured. It is rather difficult, however, to realize these favorable features. Installations for measuring flow velocities, operating on the Doppler principle and using various forms of radiation, both ultrasonic and electromagnetic (light), are described in (Ref.1, 9 - 11). The principles of operation of such systems resemble those described in (Ref.2, 3).

The velocity of a flow is determined from the magnitude of the Doppler shift of the frequency of the scattered radiation and is found by the well-known formula

$$\Delta f = 2\xi \frac{V_i}{\lambda}, \quad V \ll C_{son}, \tag{1}$$

where

V_i = projection of the velocity vector of the flow on the axis of the transmitter; /147

λ = wavelength of the incident radiation;

ξ = coefficient depending on the angle between the transmitted and the received rays;

C_{son} = velocity of ultrasound in water.

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* Numbers in the margin indicate pagination in the foreign text.

It will be clear from eq.(1) that the relative error of measurement of the mean flow velocity depends on the accuracy with which the mean frequency of the Doppler spectrum $\overline{\Delta f}$ is determined, while the sensitivity is determined by the minimum shift of this frequency that can be recorded. Naturally the value of the velocity here measured is averaged both over time and over space, i.e., over the scattering volume. The accuracy of determination of $\overline{\Delta f}$ depends on the averaging time, the form of the distribution curves of the spectral densities of the signal and noise power, and on the ratio between these powers. The density of the spectral power of noise may be considered constant in first approximation, but it may be very different for the signal (Ref.10). The maximum value of the signal-to-noise ratio at the receiver output is realized at optimum filtration.

Let us consider what determines the signal-to-noise ratio $\frac{P_{sig}}{P_n}$ at the input of the linear receiver. The electric power at the input of the receiver may be represented in the form of two summands

$$P_{in} = P_{sig} + P_n .$$

The power developed by the signal at the receiver input is

$$P_{sig} = P_r \eta_1 D_1 \eta_2 D_2 f(r) V n_1 n_2 n_c , \tag{2}$$

where

P_r = electric power applied to the radiator;
$\eta_1 D_1$ and $\eta_2 D_2$ = factors taking account, respectively, of the properties of the radiating and receiving transducers;
$f(r)$ = coefficient taking account of attenuation due to divergence and damping during propagation;
V = effective scattering volume.

The last three factors in eq.(2) characterize the scattering properties of the volume V; more specifically:

n_1 = proportion of the incident power scattered in unit volume;
n_2 = concentration of energy scattered in the direction of reception;
n_c = proportion of the coherent component of the energy scattered in the direction of reception.

The electric power of the noise acting on the receiver input may be represented in the general form

$$P_n = P_0 + P_{side} + P_d + P_{th} + P_{inco} , \tag{3}$$

where

P_0 = power of the instrument noise of the receiver input circuits;
P_{side} = noise arising in the side lobes of the radiation pattern of the receiving transducer;
P_d = dynamic noise and the noise due to flow around the instruments;
P_{th} = thermal and molecular noises; /148
P_{inco} = incoherent scattering.

The powers are summated, since the processes causing them are statistically independent. Let us evaluate each summand in the sum (3). The power of the instrument noise P_0 is determined from the Nyquist formula for $T = T_0(N - 1)$, where $T_0 = 300^\circ K$ and N is the noise factor of the receiver. Depending on the range of frequencies, N is equal to several units and may be decreased to values of 1.1 and values close to unity by the use of parametric amplification at the input. The power P_{side} entering the side lobes of the radiation pattern of the receiving transducer is determined by the scattering factor of the transducer and if it is properly designed may be very small. The power of the noise due to flow around the instruments is substantial at high flow velocities; for the ordinary values for sea velocities it may be neglected. The power of the dynamic underwater noise P_d is rather sensible at low ultrasonic frequencies. As shown in (Ref.7), with increasing frequency the intensity of this noise declines, and, beginning at frequencies of several megahertz, the thermal and molecular noises become predominant (Ref.14). The power of the incoherent scattering P_{inco} is determined by the properties of the scattering volume; it has been shown (Ref.4) to be proportional to the power of the radiation passing through, while the other components are independent of it. For this reason, by increasing the power of the radiation, we may obtain the predominance of the last summand of eq.(3) over the sum of the first four summands, i.e.,

$$P_{inco} \gg P_0 + P_{side} + P_d + P_{th} . \tag{4}$$

Then the noise at the receiver input will be determined mainly by the incoherent scattering. Under this condition the expression of the noise power at the receiver input may be written in the form

$$P_n = P_r \, \eta_1 D_1 \eta_2 D_2 f(r) V n_1 n_2 (1 - n_c). \tag{5}$$

Equation (5) differs from eq.(2) only in the presence of the factor $1 - n_c$ instead of n_c, and therefore, if condition (4) is satisfied, the signal-to-noise ratio may be written:

$$\frac{P_{sig}}{P_n} = \frac{n_c}{1 - n_c} . \tag{6}$$

This means that the signal-to-noise ratio at the receiver input is determined only by the ratio of the intensity of the coherent and incoherent components of the radiation scattered in the direction of reception. Expressions have been given (Ref.5, 6) for the coherent and incoherent scattering of continuous radiation in a homogeneous medium, and it follows from them that the share of the coherent component is very small. The value of n_c is determined by the length of the incident wave, the properties of the medium, the dimensions /149
of the scatterers, their concentration, and their distribution in the scattering volume.

Under the assumption of axial symmetry, n_c is a function only of one coordinate Θ. Since the angle Θ enters into the formula for the Doppler shift, the maximum accuracy of the system will be attained at a certain optimum value of this angle, found from the condition

$$\alpha'|_{\Theta=\Theta_{opt}} = 0,$$

where

$$\alpha = \gamma \frac{n_c(\Theta)}{1 - n_c(\Theta)} \sin\frac{\Theta}{2}.$$

Here γ is a constant; Θ is the scattering angle.

In view of the fact that the coherent scattering is most powerful at small angles of scattering, the determination of Θ_{opt} becomes very important.

It follows from the above that eq.(6) is true, provided the condition (4) is satisfied; therefore the estimate below will be true for the required radiated power

$$P_r \geqslant \frac{P_0 + P_{side} + P_d + P_{th}}{\eta_1 \eta_2 D_1 D_2 J(r) V n_1 n_2}. \tag{7}$$

Further increase of the radiated power is useless, since it will not yield a sensible improvement of the signal-noise ratio at the receiver input. Therefore, to calculate the system correctly, we must know the coefficient and indicatrix of the coherent and incoherent scattering obtained in situ for various depths and regions of the Pacific Ocean.

In view of the statistical character of the scattering process, and also for other reasons, we observe a broadening of the spectrum of the scattered radiation. Several causes of the broadening of the Doppler spectrum are considered in (Ref.10, 13). Estimates given in (Ref.13) for the value of the absolute broadening of the spectrum on account of the Brownian movement show that it need be taken into account only for scatterers of very small size and for hypersonic frequencies; at lower frequencies this broadening is negligibly small and may be neglected. The same source also gives estimates of the relative broadening of the spectrum depending on the width of the radiation patterns of disc transducers, and shows that, if the radius of the radiating surface of the transducer exceeds 10 λ, then the relative broadening will be less than 10^{-3}. These estimates, however, are true for the far zone, i.e., for

$$r > \frac{2(D+\rho)^2}{\lambda},$$

D = diameter of the radiator;
ρ = effective diameter of the scattering volume. /150

However, for the Doppler flow-velocity meters described in (Ref.9, 10), the scattering volume is in the near zone, and for this reason the broadening should be considerably greater than indicated by the author of (Ref.13). This broadening may be decreased in near-zone operation by the use of various collimator devices (Ref.8). But, in general, the relative broadening of the spectrum due to the radiation patterns of the transducers is constant for a given instrument, and may be made rather small ($< 10^{-4}$) by a rational choice of D, ρ and r.

The finite residence time of a scattering particle in the volume, and the turbulence, are the two principal causes of broadening of the spectrum of the Doppler frequencies.

Let ρ_v be the effective dimension of the scattering volume in the direction of the total velocity vector; V the modulus of the velocity vector; then the residence time of a scattering particle in the volume will be $t = \frac{\rho_v}{V}$ and the absolute width of the band of scattered radiation will be

$$\varkappa = \frac{1}{t} = \frac{V}{\rho_v}. \tag{8}$$

The relative width of the Doppler spectrum due to the finite residence time of the particle in the volume may be found by dividing eq.(8) by eq.(1):

$$\delta = \frac{\varkappa}{\Delta f} = \frac{V\lambda}{2\xi V_f \rho_v}. \tag{9}$$

On condition that the transmitter is self-aligning relative to the flow, we obtain

$$\delta \approx \frac{\lambda}{2\xi\rho_v} = \frac{1}{2\xi k_1}, \tag{10}$$

where k_1 is the effective dimension of the scattering volume in the direction of flow, in wavelengths.

Equation (10) shows that, for such a transmitter, the relative width of the bands of the Doppler spectral frequencies is independent of the velocity of the scatterers.

We note that for a transmitter aligning itself transverse of the flow, it follows from eq.(1) that $\overline{\Delta f} = 0$; but the absolute width of this band, as follows from eq.(8), is directly proportional to the flow velocity and does not depend on the wavelength. Consequently, by registering this broadening of the spectrum, $\varkappa = \frac{V}{\rho_v}$, where ρ_v is constant, we may construct a flow-velocity meter operating on a principle different from the Doppler principle, but based on the registration of the finite residence time of particles in the scattering volume.

For a transmitter self-aligned relative to the flow, we may select values /151
of k_1 in eq.(10) such that the relative broadening of the spectrum due to the finite residence time of the scattering particles in the volume shall be sufficiently small.

A further broadening of the band of Doppler frequencies is due to the turbulent structure of the flow in the scattering volume. Here, simultaneously, the result of the measurements may be considered in two different ways, depending on the scale of the process studied. If the flow velocity is determined from the mean frequency of the Doppler spectrum of frequencies $\overline{\Delta f}$, while the scattering volume is considered negligibly small in comparison with the volume of the region investigated, i.e., if the condition $L \gg \rho$ is satisfied, where L is the effective dimension of the region studied, then we shall have a Eulerian velocity of fluid flow across the point at which the instrument is situated. In the contrary case, where $a \ll \rho$, which is usually the case if a characterizes the size of the scattering particles, which may be considered as Lagrangean "fluid particles", the instrument simultaneously registers the sum of the components of the Lagrangean velocity of these "fluid particles" in the scattering volume, which is equivalent to averaging over the array, and makes it possible to verify the ergodicity for stationary processes. In this case, the absolute width of the band of Doppler spectrum corresponds to the dispersion of velocity of the particles in the scattering volume and characterizes the intensity of the turbulence on the scale of the volume:

$$\Delta F = \frac{\sqrt{\overline{\Delta V^2}}}{2\xi\lambda}.$$

Hence follows the possibility of direct measurements of the rate of dissipation of energy and the exchange coefficients. The spectrum of the Doppler signal repeats the shape of the distribution of the velocities projections of the particles, allowing for the weight contributed by them to the total signal. If the projection of the velocity of a particle and its reflecting power are independent, then gradient measurements may be made, for example, in the boundary layers.

The accuracy of such measurements depends on the ratio of the frequency bands obtained on account of the finite time of residence of the scattering particle and the band of frequencies ΔF obtained as a result of the velocity dispersion in the scattering volume. In this case it becomes possible to determine ΔF in the motion, for example, in the drift or by sounding, since ΔF characterizes the relative motion of the "liquid particles" in the scattering volume.

We note that with increasing ρ the ratio $\frac{\Delta F}{\varkappa}$ increases, since $\varkappa$ in this case becomes smaller, as follows from eq.(8), while the dispersion of velocity becomes greater. The maximum possible velocity of drift or sounding, or of oscillations in buoy installations, may be found from the condition /152

$$\frac{\Delta F}{\varkappa} > 1. \qquad (11)$$

The relative intensity of the turbulent velocity pulsations equals the relative broadening of the band on account of turbulence, i.e.,

$$\varepsilon = \frac{\sqrt{\overline{\Delta V^2}}}{V} = \frac{\Delta F}{\overline{\Delta f}},$$

where ε is determined under the condition that

$$\epsilon \geq \delta.$$

By selecting various values of ρ and λ and recording the changes in the width of the Doppler spectrum, we may investigate, at a certain distance from the instrument, the statistical characteristics of the turbulence for various scales down to the very smallest scale, while the use for such purposes, for instance, of thermohydrometers, has certain limitations, due to the finite size of the transmitter, its inertia, and the perturbation of the stream.

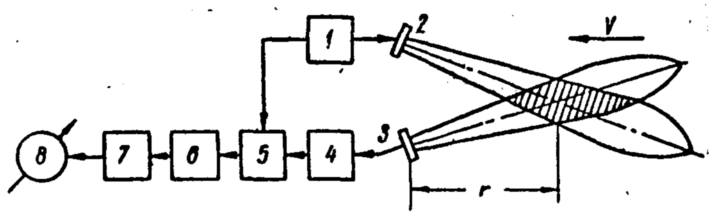

Fig.1 Block Diagram of Doppler Flow-Velocity Meter.

We shall now consider the possibility of making measurements simultaneously in different volumes of the space, and, in particular when the smaller volume is contained in the larger.

Consider several versions of the possible realization of Doppler flow velocity meters. Figure 1 shows a block diagram of a one-component Doppler flow velocity meter, based on a principle of synchronous reception. The high-frequency oscillator 1 feeds the ultrasonic radiator 2. From the scattering volume the signal is received by the transducer 3. After amplification in the high-frequency amplifier 4, it arrives at the block 5, where it is multiplied with the reference voltage arriving directly from the oscillator 1. As a result of this multiplication, two spectral bands are formed, one corresponding to the difference between the frequencies of the oscillator and the scattered radiation, and lying in the region of zero frequencies, while the mean frequency of the second band equals the sum of these frequencies. The filter 6 separates the low-frequency region from the Doppler frequencies, which, after the amplifier 7, arrive at the recorder 8. By comparison with the apparatus described in /153
(Ref.10), a meter built according to the proposed scheme has the following advantages: On separation of the spectrum of Doppler frequencies it is very important to obtain the corresponding frequency characteristics of the receiving channel, since on broadening of the frequency band more completely occupied by the Doppler spectrum, the signal-noise ratio in the band decreases. This imposes severe requirements on the shape of the frequency characteristic of the receiver tract, with respect to the steepness of the slopes and to stability. In the meter described in (Ref.10), this is attained by the use of crystal stabilization of the frequencies of the radiating oscillator and heterodyne of the receiver, while the frequency selection is accomplished on the intermediate frequency. Further than that, in this (Ref.10) system an amplitude detector is used, and therefore, on the whole, such a system must be regarded as nonlinear, and this fact must be taken into account in the analysis of the signal.

In the meter shown on the block diagram of Fig.1, no superheterodyne receiver is necessary. The receiving part of this meter may be regarded as a linear system, since in the multiplier the operation $U_{out} = U_{os}U_{sig}$ is accomplished, U_{os} being constant in amplitude, and, consequently, a simple transfer of the spectrum into the region of zero frequencies takes place. The question of frequency selection in this case is very simply solved. The pass-bands of the receiver on high frequency will be determined by the characteristic of the low-frequency filter which may be built almost ideal. Severe requirements need not be imposed on the frequency-stability of the oscillations from the oscillator, and therefore the simplest schemes of self-oscillators can be used, in particular those employing tunnel diodes. If, however, installations with a very great distance between radiator and receiver are used, it may be necessary to place them in separate containers. In this case it is possible to use separate oscillators both for the radiation and the reception of the reference frequency. The requirements for the frequency stability of these oscillators are obtained from the condition

$$\Delta f_{abs} \leqslant \Delta f_{min},$$

where

Δf_{abs} = absolute mismatch of the frequencies of the generators;
Δf_{min} = minimum frequency of the Doppler shift.

If we put Δf_{min} = 0.1 Hz, then $\frac{\Delta f_{abs}}{1} \approx 10^{-5} - 10^{-7}$ (depending on the frequency f), which is entirely attainable using quartz stabilization. The multiplication of the signals in block 5 (Fig.1) may be accomplished according to various principles, but the most suitable for these purposes is that of sign correlators and analog multipliers. Since all real multiplying schemes have /154 a finite region of multiplication, which is restricted (for example in the case of an analog multiplier, designed in the form of an annular balance modulator), by the limit of quadraticity of the nonlinear elements used, the corresponding restrictions are imposed on the amplitude of the signal and the reference frequency in analog multiplication. In particular, when semiconductor diodes are used as nonlinear resistors, their region of quadraticity is about 0.5 volt, which must be taken into account in setting up the level diagram. Since there is always direct leakage of signals from the radiator into the receiving transducer, this effect may at times impose a restriction on the values of maximum amplification of the high-frequency amplifier 4.

As already noted, in view of the statistical character of scattering, the coherent scattered signal is subject to amplitude and phase fluctuations. In the proposed installation they may be separated by adding, after the high-frequency amplifier, a second channel on the multiplier of which the reference voltage is fed with a 90° phase shift. Then the fluctuation of the amplitude of the coherently scattered signal may be found from the relation $\Delta A = A(t) - \overline{A(t)}$, where $A(t) = \sqrt{a^2(t) + b^2(t)}$.

Here a(t) and b(t) are the signal amplitudes at the output of each channel. The phase fluctuations may be determined from the relation $\Delta\varphi = \varphi(t) - \overline{\varphi(t)}$, where $\varphi(t) = \arctan \frac{a(t)}{b(t)}$.

To decrease the influence of amplitude fluctuations connected with the variation of the mean concentration of the scatterers, a system of automatic amplification control may be used.

Figure 2 is a block diagram of an installation for recording transverse pulsations of flow velocity. In this installation, the principle of autocorrelation reception is realized. This scheme may be regarded as a bridge scheme with mutual compensation of the Doppler frequencies of the longitudinal components of velocity. But it would be more correct to regard this scheme as a version of the phase method. On irradiation by the radiator 2, the particles in the scattering volume (the hatched area in Fig.2) may be regarded as sources of ultrasonic oscillations, radiating spherical waves of frequency $f = f_0 + \Delta f$, where f_0 is the frequency of the oscillator, and Δf is the Doppler shift. The receiving part of this installation is an equal-armed interferometer. The axis passing through the receiving transducers 3 and 4 is oriented normal to the flow. In this case the phase difference of the oscillations arriving at the transducers 3 and 4 is determined only by the transverse component of velocity, i.e., it does not depend on the increment Δf due to the longitudinal component. If the variation of the phase difference with time is rapid, then at the output of the multiplier 7 we obtain low-frequency oscillations of the frequency $\partial\varphi/\partial t$. /155
This scheme provides bipolar reception, and the sign of the phase depends on the direction of the transverse component of velocity. The low-frequency filter 8 passes the spectrum in the region of zero frequencies. In the simplest case, this may be the ordinary integrated RC-circuit with a time constant of several seconds or fractions of a second.

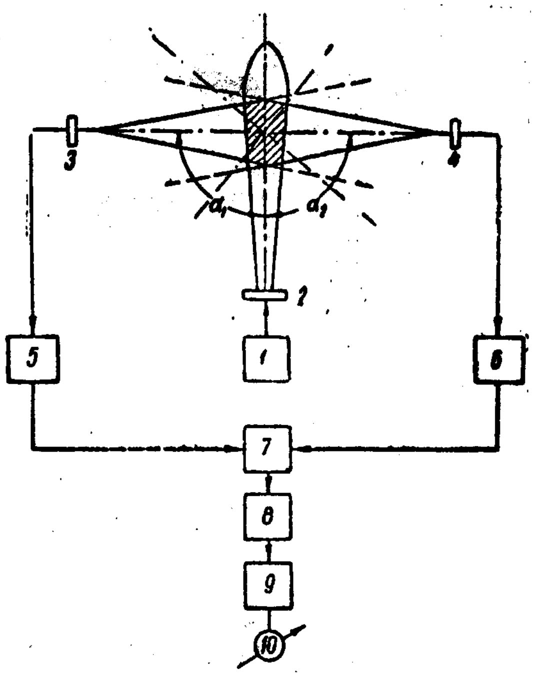

Fig.2 Block Diagram of the Doppler Meter of Transverse Pulsations of Flow Velocity.
1 - Oscillator; 2 - Radiator; 3 and 4 - Receiving transducers; 5 and 6 - High-frequency amplifiers; 7 - Multiplier; 8 - Low-frequency filter; 9 - Low-frequency amplifier; 10 - Recorder.

This system assures optimum reception, since it is a system with servo-filter. We note that in this installation the scattering volume, to eliminate parasitic pulsations, must be located on the axis of rotation of the transmitter on its self-alignment relative to the flow.

Figure 3 gives two versions of installations for investigating the spatial correlation of the velocity field. In both schemes we use a common oscillator, but the field of application of the scheme in Fig.3a is at great distances l between the scattering volumes, and that of the scheme in Fig.3b is for small values of l. The principle of operation of these installations is based on /156 the fact that part of the radiation scattered by two non-overlapping scattering volumes must be coherent (Ref.12). On coincidence of the scattering volumes, the voltage across the output of the multiplier corresponds to the power of the scattered radiation, and the scheme is equivalent to a single-channel receiver with a square detector. If the scattering volumes are separated, then the correlation declines. By shifting the transmitters by the distance l, we obtain at the output of the multiplier a spectrum of Doppler difference frequencies corresponding to the difference in the projections of the flow velocity on the axis of the installation.

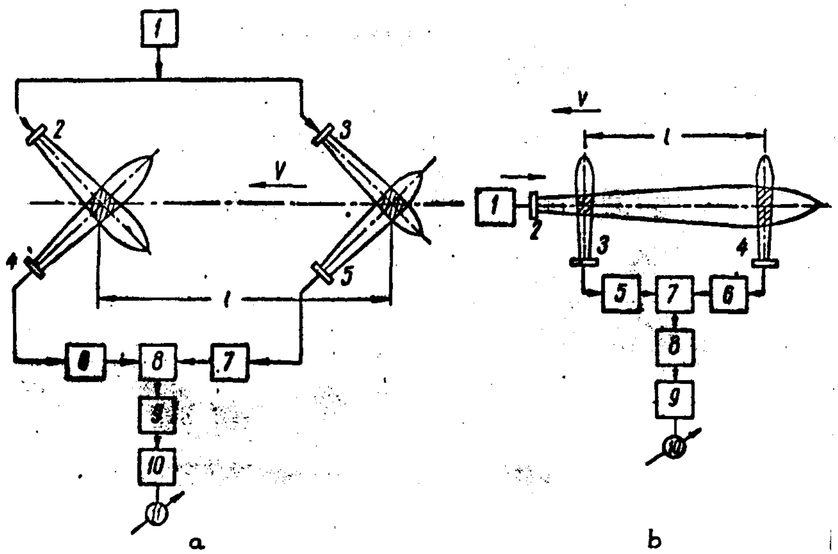

Fig.3 Block Diagram of Installations for Investigating the Spatial Correlation of the Velocity Field.
a - Installation with common oscillator and separate radiators; b - Installation with common oscillator and common radiator; 1 - Oscillator; 2 and 3 - Radiator; 4 and 5 - Receiving transducers; 6 and 7 - High-frequency amplifiers; 8 - Multiplier; 9 - Low-frequency filter; 10 - Low-frequency amplifier; 11 - Recorder.

If the condition (11) is satisfied, the velocity gradient may be recorded independently of the mean flow velocity, i.e., it is possible to make measurements in drift and in sounding. By arranging several transmitters at the same time at different distances on the base l, we can obtain the space-time statistical characteristics of the velocity field.

One of the substantial factors in Doppler flow meters is the localization of the scattering volume in space. Let us consider several methods of obtaining spatial selectivity. The most widely used is the method based on localization of the volume by intersection in space of the radiation patterns of the radiating and receiving transducers. However, with a limited instrument base, /157
this method has an insufficient resolving power along the beam. The pulse methods, widely used in radar, of obtaining spatial selectivity for measuring

the flow velocity by the Doppler method are unsuitable, since, to obtain good resolution in distance, the wave packet must be of short duration; consequently, the measure of its coherence will likewise be small, and, as shown in (Ref.6), there is no coherent scattering for the pulse signal nor an isotropic distribution of the scatterers. The application of the frequency modulation method likewise involves great difficulties, since the scattered signal contains a Doppler frequency shift.

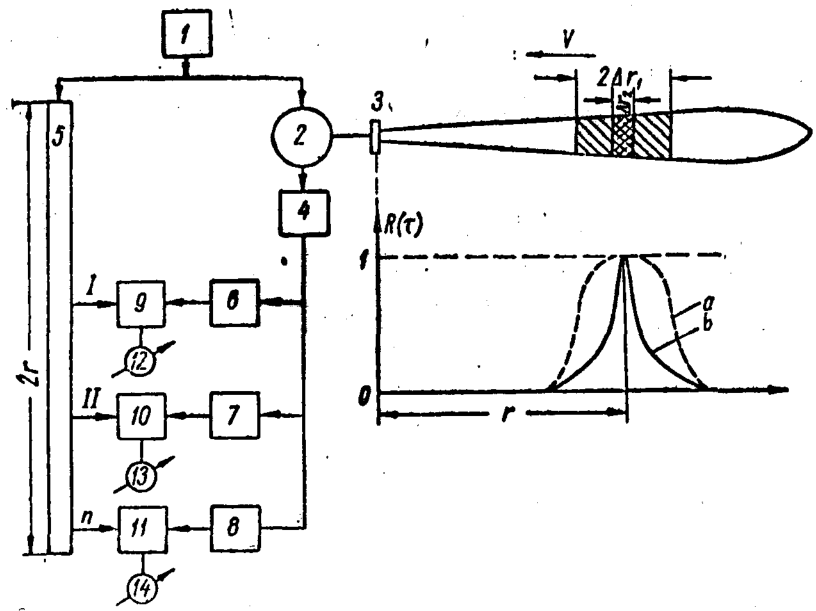

Fig.4 Block Diagram and Doppler Flow Meter, using Noise Radiation to Obtain Spatial Selectivity:
1 - Noise generator; 2 - Bridge circuit; 3 - Transducer; 4 - High-frequency amplifier; 5 - Delay line; 6, 7, 8 - High-frequency amplifiers with different passbands, 9, 10, 11 - Multiplier; 12, 13, 14 - Recorders.

Let us now consider methods of obtaining spatial selectivity, using continuous noise radiation instead of monochromatic noise radiation. Figure 4 gives a block diagram of such an installation using the principle of correlation reception [in this figure, a is the form of the function $R(\tau)$ for a narrow band and b its form for a wide band].

The noise generator (1) radiates, on a frequency ω_0, the noise voltage $U(t)$ in the band $\Delta\omega$. Part of this voltage enters the delay line (5), and the /158
remainder is fed to the bridge scheme (2). This scheme is a balanced bridge, one of whose diagonals is fed with the voltage from the generator while the other is connected with the input of the receiver. One of the arms of the bridge is the ultrasonic transducer (3). Depending on the frequency range, the bridge may be either built on the differential transformer principle or, for high frequencies, in the form of a hybrid ring. Under balance conditions, no signal from the generator (1) reaches the receiver input, but when a signal is

received by the transducers (3), the bridge is unbalanced and the signal received goes to the receiver input. Thus, the circuit ensures simultaneous operation of one transducer on reception and on radiation. The advantages of a velocity meter with one transducer are that the spectrum broadening is minimum, since $\xi = 1$ in eqs.(9) and (1); and the radiation patterns of the transducers need not be adjusted nor the angles between them calibrated. The ultrasonic noise oscillations are propagated along the beam of the transducer (3) and from each element of the volume included in the beam, while the scattered radiation is fed back to the transducer. The oscillations corresponding to this backscattering are amplified in the amplifier (4) and arrive at the inputs of the frequency filters (6), (7), (8). At the same time that the ultrasound is propagated in the medium whose velocity is to be measured, the oscillations are also propagated in the delay line (5). The multiplier (11) with the low-frequency filter is a correlator with the voltage at its output:

$$R(\tau) = \frac{1}{T}\int_0^T U(t)\,U(t-\tau)\,dt,$$

where

$$\tau = \frac{2r}{C_{con}}.$$

The signal will be maximum at the correlator output when the center of the scattering volume is separated from the transducer (3) by r which is the distance covered by the sound on its way to it and back, during the time required for propagation of the signal over the delay line (5). This distance r is determined only by the delay time t_{del} in the line: $r = 0.5\ C_{con}t_{del}$. For example, for $t_{del} = 10$ µsec, $r \approx 7.5$ m. If a hydroacoustic delay line is used, then the distance r equals half og the geometric length of the line. By varying the signal propagation time on the line, for example over the taps I and II, the scattering volumes may be simultaneously localized at different distances from the instrument. The configuration of the scattering volume in the plane normal to the beam is determined by the radiation pattern of the transducer, and in the direction of the beam by the band of noise frequencies $\Delta\omega$ and the slope of its frequency characteristic. The correlation between the spectrum and /159
the correlation function is found by the well-known formula

$$R(\tau) = \int_0^\infty G(\omega)\cos\omega\tau\,d\omega,$$

where $G(\omega)$ is the spectrum of the noise arriving at the multiplier input, and for the normal white noise of the generator is determined by the product of the amplitude-frequency and phase characteristics of both channels.

The form of the passband $\Delta\omega$ determines the form of the envelope of the function $R(\tau)$; for example, for the rectangular band $\Delta\omega$, we have

$$R(\tau) = \sigma^2 \frac{\sin\frac{\Delta\omega}{2}\tau}{\frac{\Delta\omega}{2}\tau}\cos\omega_0\tau = \sigma^2 r(\tau)\cos\omega_0\tau, \qquad (12)$$

where

σ^2 = dispersion of the signal;

$r(\tau)$ = slowly varying function under the condition $\Delta\omega \ll \omega_0$.

As will be clear from eq.(12), the function $r(\tau)$ for a rectangular band is of an oscillating damped character. More suitable is a signal with a bell-shaped frequency characteristic

$$G(\omega) = \sigma^2 e^{-\frac{\pi(\omega-\omega_0)^2}{\Delta\omega^2}}, \tag{13}$$

for which the function $r(\tau)$ is monotonously damped, i.e.,

$$R(\tau) = \sigma^2 e^{-\frac{\Delta\omega^2}{4\pi}\tau^2}\cos\omega_0\tau.$$

The function $r(\tau)$ depends on $\Delta\omega$ and determines the radius of spatial correlation Δr (Fig.4). Assuming that the radius of correlation is measured on the level e^{-1}, we obtained for the resultant Gaussian characteristic:

$$\Delta r \doteq \frac{2\sqrt{\pi}\, C_{con}}{\Delta\omega}$$

For example, for the 100 KHz frequency band, Δr = 5 cm. Thus, by selecting various values of $\Delta\omega$ and t_{del}, we can simultaneously accomplish reception from different volumes of the space located, either one in the other, or at different distances from the instrument. We note that, in this case, eq.(1) contains the mean frequency of the radiated spectrum, so that there will be a certain decrease in the modulation depth of the Doppler spectrum due to the band $\Delta\omega$. The delay lines must meet severe requirements with respect to their amplitude-frequency and phase characteristics, which must allow for the dispersion of the velocity of sound and the attenuation in the band $\Delta\omega$ during its propagation. For short distances r, hydroacoustic delay lines are possible, but for large distances r, i.e., for times $t_{del} > 1$ μsec, the delays must be on magnetic drums or magnetic tape. /160

If a source of noise radiation is used instead of the generator (1) in the installations shown in Fig.2, then the signal-to-noise ratio at the output of the system can be increased by a factor of $\sqrt{\frac{\Delta\omega}{B}}$ where $\Delta\omega$ is the frequency band of noise radiation arriving at the multiplier input and B is the passband of the low-frequency filter. The value of $\Delta\omega$ is most limited by the degree of "blurring" of the interference pattern and depends on the transverse dimension of the zone in wavelengths k_1 and on the distribution of the field intensity in the scattering volume and may be found from the following estimates.

The dependence of the modulation depth on the difference of the course for a rectangular frequency band is defined by the formula

$$M = \frac{\sin \pi \frac{k_1}{2} \cdot \frac{\Delta\omega}{\omega_0}}{\pi \frac{k_1}{2} \cdot \frac{\Delta\omega}{\omega_0}},$$

where ω_0 is the mean frequency of radiation and $\frac{k_1}{2}$ is the difference in course.

Hence, putting M = 0.63, we find

$$\frac{\Delta\omega}{\omega_0} = \frac{1}{k_1}. \tag{14}$$

For $k_1 = 100$, $\omega_0 = 2\pi \cdot 10^7 \frac{\text{rad}}{\text{sec}}$, and B = 1 - 10 Hz, we improve the signal-to-noise ratio by a factor of about 100.

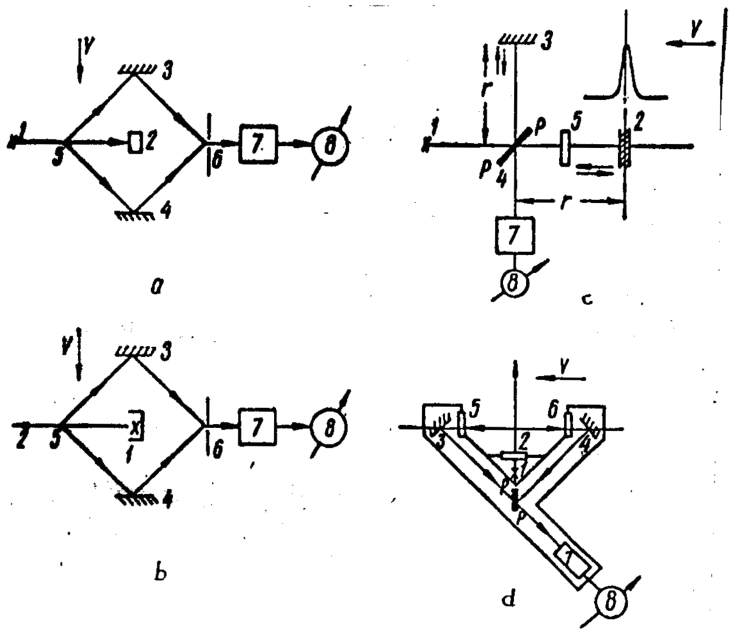

Fig.5 Diagrams of Installations for Finding the Doppler Frequency Shifts in Scattered Light.
1 - Light source; 2 - Direct ray; 3 and 4 - Mirrors; 5 - Scattered rays; 6 - Diaphragm (slit); PP - Translucent plate; 7 - Photomultiplier; 8 - Recorder.

For frequency characteristics differing from rectangular, this improvement is somewhat smaller. It follows likewise from eq.(14) that, by increasing the band $\Delta\omega$, one can also decrease the effective transverse dimension of the scattering volume which can be determined, not by the radiation pattern of radiator 2 (Fig.2), but by the relative bandwidth of noise radiation.

With respect to the application of electromagnetic oscillations (light) to find the Doppler frequency shifts in the scattered radiation, we note that if equal-armed interferometers are used, of which some variants are shown in Fig.5 for various scattering angles (a - scattering at small angles; b - scattering at large angles; c - backscattering; d - scattering at angle 90°), the stipulation that the dimensions of the light source be finite is more important than the stipulation that it be monochromatic. The spectral bandwidth can be estimated from eq.(14). For instance, at $k_1 = 1000$, the width of a radiation line for visible light must not exceed 5 - 10 Å, which is entirely attainable for ordinary spectral sources or interference filters. This makes it no longer obligatory to use lasers as the light source (Ref.11). Since the coherent /161 scattering is greatest at small scattering angles, as shown elsewhere (Ref.5), it is likewise necessary to find Θ_{opt} so as to obtain the maximum sensitivity to flow velocity. It follows (Ref.13) that the sensitivity of optical Doppler meters will be limited by Brownian movement.

It is possible, however, to measure mean flow velocities (of the order of 10^{-6} cm/sec) by combining a Doppler meter with a hydrodynamic velocity transformer. The Doppler method also permits determination of the proper motion of a suspension relative to the liquid, by simultaneous application of the Doppler and phase methods of velocity measurement, since both methods are absolute.

In conclusion, we note that the questions of recording, processing, and analysis of the signals of Doppler flow meters still require special consideration. In this case, in particular, methods of spectral analysis of radar signals reflected from planets may be used (Ref.15).

REFERENCES /162

1. Markov, M.: Morsk. Flot, No.11, p.17, 1959.
2. Vinitskiy, A.S.: Sketch of the Principles of Radar with Continuous Radiation of Radio Waves (Ocherk osnov radiolokatsii pri nepreryvnom izluchenii radiovoln). Sovetskoye Radio, Moscow, 1961.
3. Bakulev, P.A.: Radiolocation of Moving Targets (Radiolokatsiya dvizhushchikhsya tseley). Sovetskoye Radio, Moscow, 1964.
4. Sukharevskiy, Yu.M.: Dokl. Akad. Nauk SSSR, Vol.55, No.9, pp.825-828, 1947.
5. Shifrin, K.S.: Kolloidn. Zh., Vol.13, No.2, pp.129-133, 1951.
6. Kur'yanov, B.F.: Akust. Zh., Vol.10, No.2, pp.195-201, 1964.
7. Furduyev, A.V.: Akust. Zh., Vol.9, No.3, pp.265-274, 1963.
8. Martsafey, V.V.: Radiotekhn. i Elektron., Vol.10, No.3, pp.561-564, 1965.
9. Chalupnik, J.D. and Green, P.S.: Marine Sci. Instr., No.1, pp.194-199, 1961.
10. Koczny, F.F., Kronengold, M., and Loewenstein, J.M.: Marine Sci. Instr., No.2, pp.127-134, 1962.
11. Yeh, Y. and Cummins, H.Z.: Appl. Phys. Letters, Vol.4, No.10, pp.176-178, 1964.
12. Grace, J.C.: J. Acoust. Soc. Am., Vol.26, No.1, pp.103-104, 1954.
13. Green, P.S.: J. Acoust. Soc. Am., Vol.36, No.7, pp.1383-1390, 1964.
14. Ezrow, D.H.: J. Acoust. Soc. Am., Vol.34, No.5, pp.550-554, 1962.
15. Pettengill, G.: J. Res. Natl. Bur. Std., Sect.D, Vol.68, No.9, pp.1025-1029, 1964.

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